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A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies

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Abstract

Tafone-like depressions have developed on the Aoshima sandstone blocks used for a masonry bridge pier in the coastal spray zone. A thin layer of partial granular disintegration was found on the surface in depressions. To evaluate quantitatively the strength of the thin weathered layer, the hardness was measured at the surface of the sandstone blocks using both an Equotip hardness tester and an L-type Schmidt hammer. Comparison of both testing results indicates that the Equotip hardness value is more sensitive in evaluating the strength of a thin layer of weathered surface rock than the Schmidt hardness value. By applying two methods, i.e., both the Repeated Impacts Method and the Single Impacts Method, the Equotip tester can evaluate the strengths of fresh internal and weathered surficial portions of rocks having a thin weathering layer. Comparison of the two strengths enables evaluation of strength reduction due to weathering.

Key words: Equotip hardness tester, Schmidt hammer, rock strength reduction, rock weathering, sandstone

Introduction

Three decades have passed since the Schmidt hammer was introduced to geomorphological research. During this period of time considerable progress has been achieved in the field of process-oriented studies using this non-destructive measuring tool. Especially weathering studies in recent years are marked with quantitative discussion on the degree of weathering in association with reduction in

rock strength. Such progress is closely related with several advantages that the Schmidt hammer has: (1) a portable and cost effective device, (2) easy operation in the field, (3) the readings easily convertible to the most widely-used strength measure, unconfined compressive strength, and (4) non-destructive instrument, with the last becoming an advantage or not depending on the problem concerned. The potential disadvantages of the Schmidt hammer are (1) high impact energy of a plunger and (2) a large impact area. When the hammer is operated on weak material, the plunger tip sinks in the material causing considerable damage over a wide area. This does not provide accurate readings. In this context, the Schmidt hammer is not appropriate for the testing of fragile or severely weathered rock.

A new instrument, the Equotip hardness tester (Proceq, 1977, Figure 1), operates on the same principle as the Schmidt hammer, but utilizes a smaller impact energy (1/66 of that the Schmidt hammer L-type) and small impact area (7.1 mm²; the tip of spring-driven piston is made of a tungsten carbide ball with a diameter of 3 mm); and it is also of smaller size and lighter weight. The Equotip tester was originally developed to evaluate the properties of metallic materials, but it has been found to be capable of measuring the hardness of very soft materials such as fruits. This suggests that the tester can cover a wider range of measurements. It is anticipated that the Equotip may be a useful tool for furthering not only weathering research but also studies in other areas of process geomorphology and rock engineering.

Fig.1

The aim of this study is to examine rock strength paying special attention to weathering problems. To tackle these problems, the Equotip tester was applied. This article first describes reviews of the testing device used in the previous field studies on weathering, and secondly evaluates the usefulness of the device in quantifying the degree of rock weathering.

Equotip hardness tester vs. testing devices employed in previous weathering studies

To better understand landform evolution processes, the importance of quantitative investigations has been pointed out for temporal and spatial changes to physical and mechanical properties of landform materials by weathering (e.g., Yatsu, 1966; Matsukura, 1994, 1997). Weathering alters the inherent

properties of the material and reduces its strength. Generally, hard rocks do not erode easily. However, when they are weathered, their mechanical strength drops with respect to resistance to erosion. Therefore, a proposition that ‘the strength of weathered rocks controls the landform’ is of importance in landform material science in geomorphology (e.g. Matsukura, 1994). However, there are few studies focusing on the relationship between the reduction in strength due to weathering and the landform change. One of the reasons is the difficulty in evaluating the strength of weathered rocks.

The Schmidt hammer has been employed by a number of workers (e.g., Day and Goudie, 1977; Day, 1980, 1981; Matthews and Shakesby, 1984; Sjöberg, 1990, 1991a, b, 1994; Augustinus, 1991, 1992; Campbell, 1991; McCarroll, 1991; Sjöberg and Broadbent, 1991) as a means of rapidly assessing the degree of rock weathering based on the premise that, in the case of the same rock type, harder unweathered surfaces will give higher rebound values than softer weathered surfaces (Day and Goudie, 1977). The Schmidt hammer still provides a cheap, robust field tool that, if used with care, can provide an insight into weathering differences within the same lithology.

Some studies have attempted to measure a change in rock strength due to weathering using the Schmidt hammer (e.g., Suzuki et al., 1977; Matsukura et al., 1983; Mottershead and Pye, 1994; Stephenson and Kirk, 2000), needle-type penetrometer (e.g., Hall, 1987; Suzuki and Hachinohe, 1995; Hachinohe et al., 1999) and cone penetrometer (e.g., Mottershead, 1994; Yokota and Iwamatsu, 1999). Figure 2 shows the measurement limit of the three types of testing devices: L-type Schmidt hammers, needle-type penetrometers (Model SH-70, Maruto Co. Ltd., Tokyo), and cone penetrometers (Model YH62, Yamanaka Co. Ltd., Tokyo). The range of the Equotip hardness tester is also plotted. Readings of all devices are converted into unconfined compressive strength for ease of comparison. Of these three kinds of instrument, only the Schmidt hammer covers the range of medium to hard rocks (50–150 MPa). The application of this device is also possible to soft rocks with a minimum strength of 20 MPa. Application to material of lower strength is unsuitable: the impact energy is so large that rock failure may occur. Hence, the Schmidt hammer cannot be applied to assess weakly consolidated materials less than 20 MPa in compressive strength.

Fig.2

Needle-type penetrometers replace this; they cover the range of 40 MPa down to 0.3 MPa. Most of this range overlaps with that of cone penetrometers, which are appropriate for strength measurements of weakly to less consolidated materials such as soils.

As described above, the Equotip tester can be applied, as a nondestructive measuring device, to testing material strength from very weak materials such as fruits to hard matter such as metals; its measurement range is the greatest (Figure 2). It is therefore anticipated that the tester is useful for measurements of strength with a wide spectrum from extremely weathered, crumbled materials to unweathered, fresh rocks. The Schmidt hammer test, as shown before, has been the most widely used technique for research dealing with the strength of weathered rocks. A problem inherent in previous Schmidt hammer results is that they are influenced by the properties of the layer beneath that being tested. The thickness of the layer that influences the rebound value depends on the amount of impact energy, the impact area, and elastic and strength properties of the material. The Schmidt hammer produces a very high energy impact over a relatively large area such that the underlying material, up to a depth of several centimeters, may influence the rebound value. In contrast to this, the Equotip tester is found to be useful to measure the hardness of a very thin layer near the surface. Another problem of the Schmidt hammer is, due to high impact energy, it is difficult to apply to the measurement of strength of material which is so soft that it cannot rebound the plunger. The tip of the hammer sinks into the material. In this context, the Schmidt hammer test is no longer non-destructive. In contrast to this, it would be possible to quantify the hardness of such soft material using an Equotip. In next section, we present evidence of the superiority of the Equotip, through *in situ* tests at Aoshima in Miyazaki Prefecture, Japan.

In situ testing

Test site

Aoshima Island (maximum altitude: 5.7 m) is surrounded by shore platforms with an average width of about 200 m. The platforms are composed of rhythmic alternations of sandstone and mudstone of Pliocene age and are characterized by a corrugated surface with sandstone forming the ridges

Fig.3

(Takahashi, 1975). A bridge, called Yayoi Bridge, and constructed in July 1951, connects Aoshima Island with the mainland on the Nichinan coast, Miyazaki Prefecture (Figure 3a). It is aligned approximately east-west (exactly N79°E). The bridge, 130 m long, is supported by four masonry piers whose shape is the frustum of a pyramid. Each pier has four side walls facing east, south, west, and north. The south-facing wall of the second pier from the edge of Aoshima Island was selected for the present study (Figure 3a and b). The pier has a side slope of 72° and a relative height of about 3 m; its foundation, resting on a shore platform, has an altitude of 8 cm below MSL (Figure 3b). At low tide, both the base of the pier and the shore platform are exposed, while at high tide the lower zone of the pier is submerged. Mean high water level of spring tide (MHWL) is 0.8 m above MSL.

The side walls of the pier are formed of massive sandstone blocks with a size of about 35×25×35 cm, the same sandstone (named Aoshima Sandstone, i.e., fine grained Pliocene sandstone) as the shore platforms. It has a porosity of 6.9% and a dry compressive strength of 99.0 MPa (Table I).

Most of the blocks have a dish-or bowl-like depression like a tafone in their surface, the maximum depth being generally located at the centre of the block (Figure 3b). The depressions are developed in the spray zone (Takahashi et al., 1994; Matsukura, 2000). A fingertip can easily rub off some sand grains from the surface of sandstone blocks with depressions, indicating that marked weathering occurs on their surface.

Table II shows the average depression of depth for each layer, denoted here as D_{38} (the subscript 38 indicates the number of years elapsed since the construction of the pier in 1951) (Takahashi et al., 1994). The depth of the depression on the 1st and 2nd layers is quite low; it increases abruptly as the altitude increases with the 4th layer taking on a maximal value, and then decreases gradually with increasing height. However, the uppermost layer, the 11th, shows the maximum, resulting from the edge effect of weathering and/or erosion at the pier crown. The lateral variation in the depression depth shows such a characteristic pattern that the sandstone blocks at the edges of the wall have extremely large depressions. This can be attributed also to the edge effect. Excepting the top and the lateral blocks with the edge effect, seventy-eight blocks were selected for hardness

Table I

Table II

measurement.

Test results

At the end of September in 2003, hardness measurements were carried out in the field using a Type-D Equotip tester and a Type-L Schmidt hammer. Both tests followed the two methods:

Single Impacts Method: Ten rebound values were obtained from different points by a single impact and the mean of the ten values is denoted as L_s for the Equotip test and R_s for the Schmidt test.

Repeated Impacts Method: Repeated rebound values were obtained from consecutive (repeated) impacts at the same point. The number of impacts for the Equotip and the Schmidt tests were 20 and 10, respectively. The mean of the largest three rebound values is described as L_{max} for the former test, and R_{max} for the latter. This Repeated Impacts Method is proposed in our studies (Matsukura and Aoki, 2004; Aoki and Matsukura, 2007), which is a method of collecting data from a specific point by giving several impacts consecutively on the point. The measurement of several impacts is necessary to obtain the final convergent value of a test specimen. Twenty impacts in the Equotip tests and ten impacts in the Schmidt tests are needed to acquire the L_{max} value and R_{max} value, respectively.

Figure 4 shows the measurement results by repeated impacts for a sandstone block that is located on the 4th layer from the base of the pier and the 6th from the western side of the wall under investigation. The scale of the y-axis of this graph is normalized for comparison. The first impact values for both tests are similar and lowest in each set of consecutive data. This strongly suggests that the first value, reflecting the hardness of a thin surface layer, represents the strength of weathered material. Both Equotip- and Schmidt-values increase with increasing number of impacts. The former attains a maximum at the 12th blow, while the latter at the fourth impact (the arrows in Figure 4).

Fig.4

The impact energy of the Equotip tester is only 1.5 % of that of the L-type Schmidt hammer. The number of impacts to reach the maximum is larger in the Equotip than the Schmidt hammer test.

This would be closely associated with the magnitude of impact energy. The lower energy of the Equotip tester causes much slower and narrower compaction of the surface layer to facilitate a slower increase in rebound values with larger number of impacts.

It is reasonable to assume that both L_{\max} and R_{\max} represent the hardness of the deepest part (i.e., unweathered portion) of the sandstone block. Figure 5 shows the relationship between the two quantities using data obtained from the sandstone blocks. The value of L_{\max} ranges from 466 to 723, while R_{\max} from 35 to 56. The L_{\max} value increase generally with increasing R_{\max} , as indicated by the straight line depicted based on the reduced measure axis method, the coefficient of the correlation is 0.754. The large scatter of data points suggests that there is considerable difference in strength among individual sandstone blocks used for the pier.

Fig.5

Next, correlations between data obtained by the two measuring methods are examined for the Schmidt hammer test (Figure 6a) and for the Equotip test (Figure 6b), respectively. Comparison of these two diagrams indicates that the Schmidt hammer data show a higher correlation (0.867) than that of Equotip test (0.511). This can be ascribed to the difference in the magnitude of impact energy. The Schmidt hammer generates so much energy, as compared with the Equotip, that it penetrates deeper to the central part of a test block, which implies that the rebound value of single impacts in Schmidt tests, i.e., R_s , must represent the hardness of the internal unweathered portion as well as the strength of the superficial weathered layer. Therefore, the Schmidt hammer testing is likely to be inappropriate to evaluate the hardness of a thin weathered surface layer. A poor correlation in the Equotip diagram (Figure 6b) suggests that L_s has a wide range of rebound values, reflecting the varying hardness of the weathered part of the surface layer. This confirms that the Equotip is a useful tool for the study of strength of surfacial weathered material. The Equotip is also more sensitive to the difference between the lowest and highest strengths.

Fig.6

Evaluation of rock strength reduction with the Equotip hardness tester

As described above, the Equotip tester appears superior to the Schmidt hammer for identifying surface rock strength. Weathered sandstone blocks composing the pier can not be removed to

furnish a test specimen. Instead, a weathered sandstone block from the shore platform around the pier was sampled and a test specimen was prepared in the laboratory. The block was sampled with a dimension of approximately 10 x 12 x 25 cm. The section of the rock sample split through the center with a cutting tool shows an unweathered part in its central portion surrounded by a thin weathering layer (Figure 7a). Figure 7b shows the microscope photograph of a sectional view of the edge of split surface, indicating that the weathered surface has micro undulations made of some protruding sand-grains (white arrows in figure) with a diameter of ca. 0.1–0.2 mm and cracks (black arrows in figure) with a depth of ca. 0.5 mm. This photograph shows the thickness of weathering layer ($0.5 + 0.2 = 0.7$ mm) corresponds to the several layers of sand grains. These observations suggest that granular disintegration actively occurs at the surface and in the outermost layer by removing the matrix materials and/or reducing intergranular bonding due to salt weathering. Although the tip ball of the Equotip has a diameter of 3 mm which corresponds to the four or five times larger than the thickness of the weathered layer, the measure value of the instrument seems to reflect the strength of the weathered layer.

Fig.7

Equotip measurements were conducted on both the weathered (Area A in Figure 7a) and the unweathered surfaces (Area B in Figure 7a) by the Repeated Impacts Method (consecutive twenty impacts on the same point) and Single Impacts Method (ten individual impacts on different points). Figure 8 shows the results. The rebound values obtained, from both the weathered and unweathered parts of the sample, increases as the number of impacts increases. It should be noted here that the first impact values of the weathered and unweathered portions are clearly different (443 for the former and 551 for the latter), but L_{\max} , the mean of the largest three values during the measurement, shows similar values (716 for the former and 720 for the latter). The value of L_{\max} thus defined designates the hardness of the unweathered interior of the rock.

Fig.8

Figure 8 indicates that L_s , the mean of ten single impacts on different points, has a value of 450 for the weathered part, and 554 for the unweathered portion, both having some degree of scatter in the measurement, which is depicted by the length of vertical bar attached to the data point. It is expected that these show similar values, respectively, to the initial values in the repeated impacts

testing.

Figure 8 also shows that L_s is lower than L_{max} even on the fresh part of the rock sample. Aoki and Matsukura (2007) examined the relationship between L_s and L_{max} for various fresh rock specimens, and the k -value ($= L_s/L_{max}$) is found to vary between rock samples, reflecting strength characteristics inherent in them, such as the consolidation of mineral grains, the looseness of the original rock surface, and the degree of compaction due to repeated impacts. In the case of the fresh sample of Aoshima sandstone, k was 0.78. The present test shows that the values of L_s and L_{max} for the unweathered fresh part are 554 and 720, respectively (Figure 8). The value of k calculated using these values is 0.77, which coincides with the value of the preceding test, 0.78.

The values of L_s from the weathered and unweathered parts are 450 and 554, respectively. The value on the weathered surface is lower by approximately 100 than that on the fresh portion, and the k -value is 0.63. The difference between the two is considered to reflect the degree of weathering. Unless such a specimen as shown in Figure 7, with a split surface through the unweathered part, is available, the direct measurement of L_s -value from the fresh part is impossible. In this case, an indirect estimation of this value is possible if the k -value ($= L_s/L_{max}$) of the fresh rock sample has been determined, since L_{max} of the fresh rock is equal to the L_{max} value obtained from a specimen with a thin weathering layer through a repeated test, as described before.

At Aoshima, the removal of the sandstone blocks forming the pier is not allowed, so that the direct measurement of L_s is not available. The present study follows the indirect estimation procedure mentioned above. From the *in situ* measurement of L_{max} on the seventy-eight blocks plus the blocks forming the 1st and 2nd layers, and by using the relation $k = 0.77$, the value of L_s was obtained by multiplying L_{max} by 0.77 and the value thus calculated is denoted as L_{intact} . To avoid confusion, the rebound value from the weathered surface of the sandstone blocks by the Single Impacts Method is hereafter referred to as $L_{surface}$, unless otherwise stated.

Figure 9 shows the relationship between $L_{surface}$ and L_{intact} for two zones: the intertidal and spray zones. The bold line denotes $L_{surface} = L_{intact}$, indicating no weathering. The family of lines is plotted with different values of δ in the following equation:

Fig.9

$$L_{\text{surface}} = \delta L_{\text{intact}} \quad \text{or} \quad \delta = L_{\text{surface}} / L_{\text{intact}} \quad (1)$$

The value of δ indicates the degree of weathering, i.e., the ratio of strength reduction. There are various degrees of weathering as shown in this figure. The surface of sandstone blocks immediately after suffering erosion has a higher value of L_{surface} , which results in a higher δ -value. When considering the strength reduction due to weathering, therefore, the minimum value in the data cluster of each zone is of significance. Figure 9 shows that $\delta = 0.67$ for the spray zone and 0.76 for the intertidal zone. The results indicate that the strength of a block in the spray zone has been reduced to 67 % of the strength of unweathered fresh part, and in the intertidal case it has rendered 76 %. Figure 10, a similar diagram to Figure 9, indicates that the lower value of L_{surface} in the spray zone is approximately 320, which is lower than the value for the intertidal zone, 361, both being independent of the value of L_{intact} . Figures 9 and 10 illustrate that weathering is more active in the spray zone.

Fig.10

Conclusions

The conclusions of this study that examined an application of the Equotip hardness tester, originally developed in the field of metallic engineering, are as follows:

(1) The Equotip tester is a portable, simple, non-destructive measuring tool that can be employed in field investigations. The measurement range of the Equotip tester is the widest of the existing tools available for geomorphological use and the Equotip testing can be applied to almost all rocks (from weathered rocks to fresh hard rocks).

(2) Comparison of test results indicates that the Equotip hardness value is more sensitive to evaluate the strength of a thin layer of weathered rock surface than the Schmidt rebound value. This suggests that measurement by Equotip testing is effective for estimating degree of strength reduction due to weathering. By applying both the Repeated Impacts Method and the Single Impacts Method, the Equotip tester can evaluate the strengths of fresh internal and weathered surficial

portions of rocks having a thin weathering layer. Comparison of the two strengths enables one to evaluate the strength reduction due to weathering.

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List of Figures& Table

Figure 1. The Equotip impact device. The Equotip hardness tester, which is introduced by Proceq, S. A., is an electronic battery-operated, spring-loaded device. A spring-driven piston, the tip of which is mounted with a tungsten carbide ball with a diameter of 3 mm, plunges towards the surface of material to be tested. The impact energy is 11 Nmm and is found to be *ca.* 0.5 % of that of the N-type Schmidt hammer, and the impact area is 7.1 mm². Equotip is manufactured by Proceq SA Co. Ltd. in Reisbachstrasse 57 CH-8034 Zurich/Switzerland.

Figure 2. Measurement ranges of Equotip hardness tester, Schmidt hammer, needle-type penetrometer (Model SH-70, Maruto Co. Ltd., Tokyo), and cone penetrometer (Model YH62, Yamanaka Co. Ltd., Tokyo).

Figure 3. (a) Aoshima Island and Yayoi Bridge, viewed from the southwest; and (b) Erosional features of the south-facing wall of the studied pier. M.H.W.L. and M.S.L. denote the ‘mean high water level’ and ‘mean sea level’, respectively. The numbers indicate the number of the layers of the stone masonry above the foundation: 1 is the first layer, 5 is the 5th layer and 10 is the 10th layer. The first to 3rd layers are located in the intertidal zone, and the layers above the 4th in the spray zone.

Figure 4. Changes in the normalized rebound value of Equotip (L -value) and Schmidt hammer (R -value) with the number of repeated impacts at the same point.

Figure 5. Relationship between R_{\max} - and L_{\max} -values.

Figure 6. a) Relationship between R_{\max} - and R_s -values and b) between L_{\max} - and L_s -values.

Figure 7. a) Aoshima sandstone block used for calibration of Equotip rebound value of fresh surface (Area A) and weathered rock surface (Area B): split surface was cut by a diamond saw. b) Sectional view of the edge of split surface. Sandstone is mainly composed of quartz grains having a diameter of 0.1–0.2 mm. Micro-undulation due to protruding sand grains (white arrows) and cracks (black arrows) seems to be formed by granular disintegration due to salt weathering. Photograph shows that the weathering layer has a thickness of about 0.5–0.7

mm.

Figure 8. Rebound values of Equotip (L -value) on weathered surface and split surface of Aoshima sandstone block.

Figure 9. Relationship between estimated L -value of fresh rock (L_{intact} -value) and measured L_{surface} -value.

Figure 10. Relationship between estimated L -value of fresh rock (L_{intact} -value) and measured L_{surface} -value.

Table I Some physical and mechanical properties of Aoshima Sandstone (after Takahashi, 1975).

Table II Location of sandstone block layer and the average depth (D_{38}) during 38 years for each layer (Takahashi et al., 1994).